Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 5 (2010) 633–636
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

Optical Performance of B-layer Ultra-shallow-junction Silicon Photodiodes in the VUV Spectral Range

L. Shi[a,]*, F. Sarubbi[a], L. K. Nanver[a], U. Kroth[c], A. Gottwald[c], and S. Nihtianov[a,b]

[a] *Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands*
[b] *ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands*
[c] *Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, D-10587, Berlin, Germany*

This work is supported by The Dutch Technology Foundation STW, project number: 10024.

Abstract

In recent work, a novel silicon-based photodiode technology was reported to be suitable for producing radiation detectors for 193 nm deep-ultraviolet light [1] and for the extreme-ultraviolet (EUV) spectral range [2][3]. The devices were developed and fabricated at the Delft Institute of Microsystems and Nanoelectronics (DIMES), TU Delft. In this paper, we characterize the optical performance of the DIMES photo-detectors in the vacuum-ultraviolet (VUV) spectral range, in particular between 115 nm and 215 nm wavelength. We report an outstanding performance in terms of low dark current, high responsivity and irradiation stability. Owing to these features, the presented photodiode technology, which profits from low cost, reduced complexity and full compatibility with standard Si processing, offers a reliable solution for the implementation of detectors in applications making use of VUV radiation.

Keywords: photodiodes, vacuum-ultraviolet, radiation detectors, responsivity, ultra-shallow junctions.

1. Introduction

Nowadays, the demand for radiation detectors in the VUV spectral range (wavelengths below 200 nm) is noticeably increasing. For example, the ever decreasing feature size of the projected patterns on silicon wafers has led to the development of 193 nm wavelength lithography [4]. The metrology and the dose control of the VUV pulsed sources require the use of sensitive VUV radiation detectors. Therefore, the development and the fabrication of high-performance detectors for VUV radiation are becoming important for the future of nanoelectronics manufacturing.

Due to the low cost and well-developed technology, Si-based photodiodes are good candidates for the above mentioned applications. The extremely small penetration depth of the VUV radiation in silicon, as shown in Fig. 1, requires the depletion zone of the photodiode, where the photo-generated charge is collected, to be very close to the device surface [5]. The DIMES silicon-based photodiodes have an ultra-shallow junction depth of only a few nm and therefore they have a great advantage for radiation detection in the VUV spectral range.

2. Device description

Fig. 2(a) presents a photograph and a schematic cross-section of DIMES photodiode. As indicated in the

doi:10.1016/j.proeng.2010.09.189

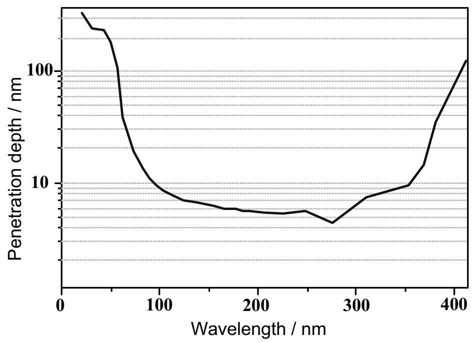


Fig.1. Penetration depth vs. incident radiation wavelength in Si.

schematic cross-section, a low-doped (< 10^{14} cm^{-3}) epitaxial layer is grown on a 1-10 Ωcm n-type Si(100) substrate. The epi-layer thickness sets the breakdown voltage and junction capacitance of the diodes and can be adjusted for specific applications. On the epi-layer, the diode anode, which is the delta-doped boron surface layer, is selectively deposited in an opening through an SiO_2 layer, by using a pure boron atmospheric/low-pressure chemical vapor deposition (AP/LPCVD) at 700 ºC with diborane (B_2H_6) as the gas source [1]. Fig. 2(b) shows a high-resolution TEM image of the B-layer formed after a 2.5 min B_2H_6 exposure along with the corresponding Boron SIMS profile. The boron coverage is uniform and form the electrical characterization of the p^+n diodes it has been determined that there is a well-controlled, ultrashallow p^+ doping of the Si surface within a depth of a few nanometers [1][2]. Additional coating layers can be deposited on the B-diode surface, for protection, anti-reflection, or to facilitate the integration of thin film filters with radiation pass-bands optimized for specific applications.

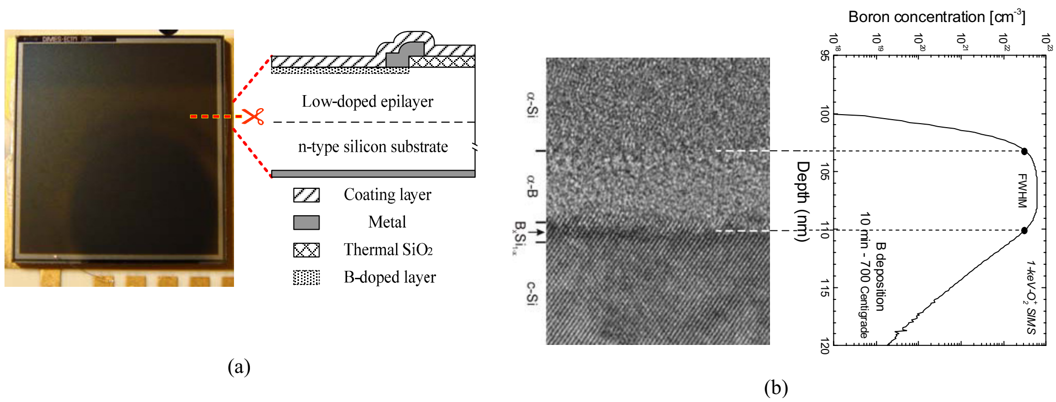


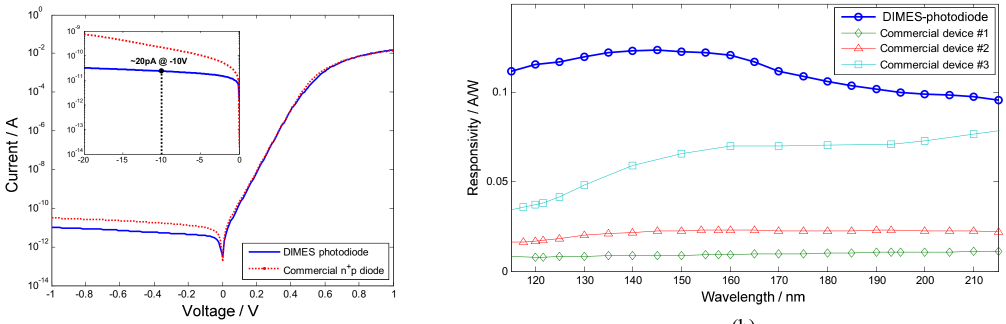
Fig.2. (a) Image and cross-section of DIMES photodiodes (Active area size ~ 1×1 cm). (b) HRTEM image of a B-layer formed after a 10 min B deposition at 700 ºC with a Boron SIMS profile. The sample has been covered with 20 nm PVD α-Si for the TEM analysis.

3. Measurement and characterization

In this section, we illustrate the electrical and optical performance of the fabricated VUV photodiode and demonstrate the fundamental advantages of the pure boron CVD deposition for VUV radiation detection. DIMES photodiodes are also compared to some commercially available devices, which are representative of the current state-of-the-art UV silicon photo-detectors.

3.1. I-V characteristics

Fig. 3(a) shows the I-V characteristics of a Boron-doped p^+n diode as compared to a commercially available n^+p photodiode. Both measured diodes have the same circular geometry and a diameter of 3.7 mm. Excellent electrical performance is achieved in terms of low dark current (< 50 pA at a reverse bias of 10 V) and ideality [2], as expected for a defect-free p^+n junction.

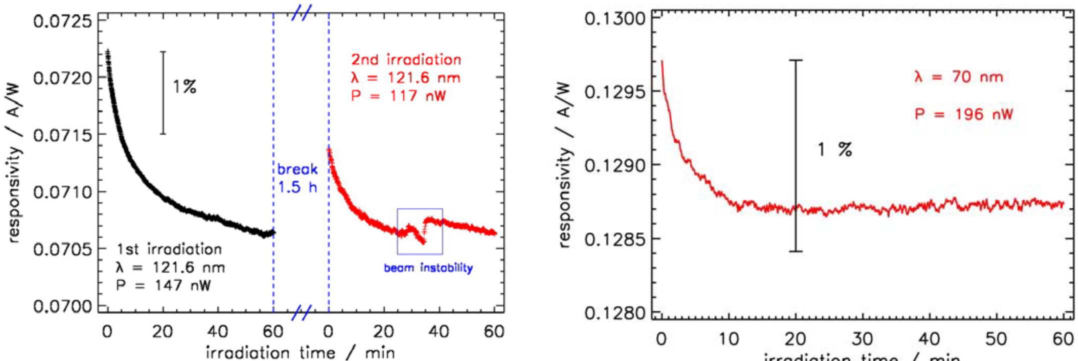


(a) (b)

Fig.3. (a) I-V characteristics of the DIMES as deposited DIMES photodiode compared to a commercial n^+p photodiode. The inset shows the dark current with reverse bias up to 20 V. (b) Responsivity of the DIMES photodiode in VUV spectral range compared with other state-of-the-art photodetectors.

3.2. VUV optical performance

Optical tests were carried out at the synchrotron radiation laboratory of PTB (Physikalisch-Technische Bundes-anstalt) in Berlin, Germany [6][7]. Fig. 3(b) shows the superior responsivity of the DIMES photodiode compared with other state-of-the-art photodiodes in the VUV spectral range (wavelengths from 115 nm to 215 nm) [8][9][10]. This excellent optical performance confirms that the B-deposition process can provide ultra-shallow and high-quality p+-doped active surface layers, which can effectively enhance the quantum efficiency by reducing the VUV photon absorption in the front window.



(a) (b)

Fig.4. Degradation of the responsivity of DIMES photodiodes during irradiation at 121.6 nm (a) and at 70 nm (b).

The degradation under irradiation of the DIMES photodiodes was characterized by a two-hour irradiation at 121.6 nm wavelength, followed by a one-hour irradiation at 70 nm wavelength. Fig. 4(a) and 4(b) show the spectral responsivity of the diode monitored during the irradiation. As indicated in the figures, responsivity decreases of about 2 % and less than 1 % were observed for the 121.6 nm wavelength irradiation and the 70 nm wavelength irradiation, respectively. This initial small reduction of responsivity is followed by what appears to be a saturation of the degradation. In Fig. 4(a), within the 1.5 hour break between the two exposure runs, a regeneration of the responsivity could be clearly seen. In general, based on above experimental results, no significant responsivity degradation was observed on the DIMES VUV photodiode. Therefore, we can conclude that the boron surface layer is robust to VUV exposure.

4. Conclusions

In summary, we have presented a high-performance silicon-based photodiode technology for VUV radiation detection that offers excellent electrical and optical performance in terms of extremely low dark current, outstanding responsivity, and high stability to VUV radiation exposure. Such impressive features are achieved by forming ultra-shallow boron-doped layers on the active area with a novel CVD doping technique which ensures the integration of high-quality p^+n junctions. In addition, the process offers considerable flexibility in optimizing the device performance in relation to specific application requirements. Comparisons with commercially available VUV detector solutions show that the B-deposited photodiodes perform with superior characteristics and exhibit a great potential for radiation detection in VUV-based application, such as in 193 nm lithography systems.

Acknowledgements

The authors would like to thank the staff of the DIMES-ICP cleanrooms and measurement room for their support in the fabrication and measurement of the experimental material.

References

[1] F. Sarubbi, L. K. Nanver, T. L. M. Scholtes, and S. N. Nihtianov, "Extremely Ultra-Shallow p^+-n Boron-Deposited Silicon Diodes Applied to DUV Photodiodes", in *Proc. 66th Device Research Conference (DRC)*, 2008.

[2] F. Sarubbi, L. K. Nanver, T. L. M. Scholtes, S. N. Nihtianov, and F. Scholze, "Pure boron-doped photodiodes: a solution for radiation detection in EUV lithography", in *Proc. IEEE 38th European Solid-State Device Research Conference (ESSDERC)*, pp. 278-281, Sept. 2008.

[3] L. Shi, F. Sarubbi, S. N. Nihtianov, L. K. Nanver, T. L. M. Scholtes, and F. Scholze, "High performance silicon-based extreme ultraviolet (EUV) radiation detector for industrial application", in *Proc. 35th Annual Conference of the IEEE Industrial Electronics Society (IECON), Porto, Portugal*, Nov. 3-5, 2009, pp. 1891-1896.

[4] International Technology Roadmap for Semiconductors: Lithography, 2007 Edition. Available at: http://www.itrs.net.

[5] US Patent 7 586 108, Radiation detector, method of manufacturing a radiation detector and lithographic apparatus comprising a radiation detector, September 8, 2009

[6] A. Gottwald, U. Kroth, M. Richter, H. Schöppe, and G. Ulm, "UV and VUV detector-based radiometry at the MLS", submitted to *Meas. Sci. Technol*. (2010).

[7] A. Gottwald, U. Kroth, M. Krumrey, M. Richter, F. Scholze, G. Ulm, "The PTB High-Accuracy Spectral Responsivity Scale in the VUV and X-Ray Range", *Metrologia 43*, S125-S129 (2006)

[8] M. Richter, U. Kroth, A. Gottwald, C. Gerth, K. Tiedtke, T. Saito, I. Tassy, and K. Vogler, "Metrology of pulsed radiation for 157-nm lithography", *Appl Opt*. vol. 41, no. 34, pp. 7167-7172, Dec. 2002.

[9] L. R. Canfield, R. E. Vest, R. Korde, H. Schmidtke, and R. Desor, "Absolute silicon photodiodes for 160 nm to 254 nm photons", *Metrologia*, vol. 35, p. 329, 1998.

[10] K. Solt, H. Melchior, U. Kroth, P. Kuschnerus, V. Persch, H. Rabus, M. Richter, and G. Ulm, "PtSi-n-Si Schottky-barrier photodetectors with stable spectral responsivity in the 120-250 nm spectral range", *Appl. Phys. Lett.*, vol. 69, no. 24, pp. 3662-3664, Dec. 1996.